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Objective design for miniature fiber-optic image-beam endoscope

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Abstract: According to the requirements of small size and large field of view of the micro-fiber soft mirror, the design criteria were analyzed, and the "negation-positive" type reverse telephoto objective was used as the initial structure to determine the image side telecenter optical system. Through theoretical calculation and optimization of Zemax optical simulation software, a miniature fiber optic beam endoscope objective with the operating band of 0.48um ~ 0.65um, focal length of 0.37mm, full field of view of 90° and relative aperture of 1:4 was designed. The objective lens is composed of four lenses, including one negative lens, one positive lens and one double glue lens. The design results show that the total length of the lens is 3.89 mm, and the maximum cross section diameter is 0.95 mm, which meets the initial design requirements of the image side telecentric optical system. The modulation transfer function (MTF) at the Nyquist spatial frequency of 77 lp/mm is approximately 0.7. It is close to the diffraction limit, and has the characteristics of small size, large field of view, good image quality, reasonable structure, and uniform illumination intensity on the image plane, which is suitable for the use of miniature fiberoptic endoscope.

Key words: Applied optics; Xiang Yuanxin; Optical fiber image transmission bundle; Objective lens; Limiting resolution

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Objective lens design of subminiature endoscope with image fiber bundles

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Abstract : According to the requirements of small size and large field of view(FOV) for subminia-ture fiber soft endoscope, the fundamental design criteria was analyzed, the retrofocus objective with a "negative-positive" form was utilized as the initial structure, and the telecentric optical system in image space was determined for this design. Through theoretical calculation and con-tinuous optimization with Zemax optical design software , a designed subminiature endoscope ob-jective lens sample was fabricated finally, with operation wavelength, focal length, FOV and rel-ative aperture of 0. 48 µm-0. 65 µm, 0. 37 mm, 90° and 1: 4, respectively. The optical system is composed of 4 pieces of lenses, including two single lenses and one cemented doublet. The re-sult shows that its total length is 3. 89 mm and maximum cross sectional diameter is 0. 95 mm, which can satisfy the initial design requirements of image telecentric structure. The modulation transfer function (MTF) value of the lens is approximately 0.7 at Nyquist spatial frequency of 77 Ip/ mm, near the diffraction limit. Furthermore, the designed lens has the peculiarity of wide FOV, short focal length, fine quality of imaging, reasonable structure and uniform illumination at im-age plane. It is suitable for the subminiature fiber endoscope demand.

Key words : applied optics; telecentric image space ; imaging fiber bundle; objective; limiting resolution

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Introduction

Endoscope with the progress of science and technology constantly improve, in industrial manufacturing, machinery processing, power electronics, civil engineering and construction and a series of related fields has been widely used, especially in the field of medical, endoscopic become indispensable in daily medical and surgical equipment. Since 1853, when French surgeons invented the first endoscopic device, endoscopic technology has been constantly developing. In recent years, the development of endoscopes has produced more forms: microfiber endoscopes, ultra-long video endoscopes, multi-elbow tube detection endoscopes, stereo dual-channel endoscopes, etc. At present, the foreign research and development and production technology of various endoscopes has been quite mature, such as the LD fiber endoscope of the British ultra-fine Technology company, with a resolution of up to 30 lp/mm~50 lp/mm and a diameter of only 0. 34 mm. Olympus of Japan and Wolves of Germany have achieved great success in the development and production of fiber endoscopes. Since the 1970s, China has gradually carried out the research and development of industrial and medical endoscopes applied in different occasions. Among them, Li Dongyuan et al., from Yanshan University, designed a hybrid fold-diffractive optical system, which improved the image quality through the introduction of aspheric lens, so that the overall volume and quality of the system were controlled, so as to obtain a fiber-coupled objective with large field of view and small aberration, but its material and processing costs were high [. According to the requirements of the new industrial endoscope, Changchun University of Science and Technology designed the overall optical system, but the field of view Angle of the objective lens was only 602. With the emergence of new materials and the continuous progress of processing technology [31], Changchun University of Science and Technology designed a dual-band optical fiber image transmission system. Can be carried out within the visible light and near infrared image acquisition, marked the infrared optic imaging technology is gradually mature 5. In recent years, university, Chinese Academy of Sciences, Chinese Academy of Sciences, xi 'an light machine for fiber endoscope by optical system also has carried on the corresponding research, and has made remarkable achievements, but also has the difficulty in viewing Angle or relatively large size [6. In the field of research and development and manufacturing of optical fiber image transmission beam, Changchun Institute of Optical Machinery, Xi 'an Institute of Optical Machinery and Nanjing Chunhui are all in the leading position in China.

The optical fiber image transmission beam in fiber endoscopy is a passive device formed by assembling a certain number of optical fibers with the same length according to a certain arrangement, after curing and polishing. It is light in weight, can be bent at any Angle, and can carry out image transmission in complex space. It has been widely used in various fields such as medical treatment, industry, scientific research, aerospace, military and so on. In fiber type a prerequisite for the endoscopic optical system, a prerequisite for the object through the corresponding objective would transmit the imaging in people like fiber beam of light on the face, again through the single fiber as a like yuan for image transmission, and each optical fibers with excellent optical insulating properties, can separate the images and interference from adjacent optical fiber. Therefore, the image of the incident surface of the fiber optic beam can be regarded as an independent sampling of the image generated by the coupled objective lens through a single fiber. The sampling points are the pixels composed of the fiber beam, and the size and number of pixels are the size and number of sampling points. The optical fibers of the two end faces of the image transmission beam are arranged regularly according to a certain arrangement, so that the images of the two end faces are basically the same. After the outface is combined with the first mirror for direct observation by human eyes, or connected to the image system behind the eyepiece, the image is processed by the image equipment and directly observed on the display [10].

1 Principle of Design

Some special purpose fiberoptic medical endoscopes enter the human body from a narrow cavity for observation, diagnosis and surgery, so their appearance size has certain restrictions. As the main component of the image transmission system, the optical fiber image transmission beam is much smaller than the traditional large section optical fiber image transmission beam, and it requires better imaging quality and larger objective Angle of view, so the structure and size of the front objective lens are put forward higher requirements.

In the design process of fiberoptic endoscope objective lens, according to its design requirements, the optical characteristics are analyzed, and the anti-far E-type structure is considered. The inverse distance structure is asymmetric, and the front group of lenses with negative focal degree deflector the light outside the axis, so that the back group of lenses has a small field of view, so as to meet the design requirements of ultra-wide Angle. In general optical systems, the aperture light bar can be placed in a variety of ways. In the anti-far E-type optical system, if it is placed in the front group of the lens, because it is too close to the entrance pupil, the front group lens cannot be deflect the off-axis light, resulting in the size of the back group lens increasing. In order to make the front objective lens have a smaller appearance size and lighter mass, the aperture light bar is generally placed on the back lens to form a "negative-positive" type of reverse distance optical system [1].

According to the total reflection theorem, when A beam of light is emitted from the light dense medium to the smooth interface of the light hydrophobic medium, the pinch between the incident light and the interface normal is greater than or equal to the adjacent Angle, and all the beam emitted by A will be reflected into the light dense medium. The optical fiber of the image beam is made according to the law of total reflection. Therefore, in the design process of the optical system of the fiber endoscope objective lens, it is necessary to ensure that the numerical aperture of the image beam fiber and the incident light can match each other. As shown in Figure 1. Target AB in image transmission optical fiber beam through A lens imaging A 'B', as image transmission Angle is equal to the beam of numerical aperture of the optical system like party numerical aperture Angle, for imaging beam axis AA ', AA 'imaging beam of optical axis symmetry and shooting incident directly to the optical fiber surface, axial AA' can all into A beam of image transmission optical fiber; But for the off-axis beam BB, its imaging beam is opposite

Since the off-axis light RBB is oblique incident on the plane A of the image beam fiber at the Angle of w, part of the off-axis BB' light cannot enter the image beam fiber, resulting in the image beam fiber can not receive this part of the light, resulting in the output image edge band is dark. And with the increase of the field of view, the effect is more obvious.

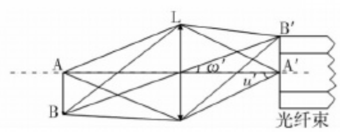

Figure 1 Image input of the optical fiber image transmission bundle

Fig. 1 Image input of imaging fiber bundle

In order to ensure the image quality of the imaging fiber bundle, the front objective lens should consider selecting the image side telecentric optical path system 2, as shown in FIG. 2. As the main light and optical axis is parallel to each other, and off-axis beams on BB and axis AA 'all the imaging beam can into people like beam propagation in optical fiber, the optic like a bunch of input and output of the image intensity distribution, at the same time to ensure the system like fangyuan's heart outside the shaft and the shaft like face illumination uniformity, makes the image transmission optical fiber beam of image quality is improved.

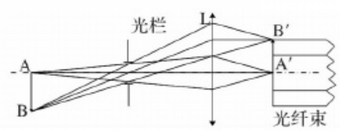

Figure 2 The pre-telecentric optical system of the optical fiber image transmission beam

Fig. 2 Front telecentric optical system of imaging fiber bundle

The limiting resolution of the image beam is one of the key parameters that affect the imaging effect of the front telecentric optical system of imaging fiber bundle. According to the research theory of image beam fiber, it is known that the end diameter of the single fiber of the image beam d, the arrangement of the single fiber of the image beam and the glue spacing determine the limit resolution of the image beam. As shown in Figure 3, square or hexagon combinations are often used in the preparation of optical fiber image transmission beams. When the optical fiber image transmission bundle is static, the combination of the square is used, and its limit resolution is

$$\sigma_{正}=\frac{1}{2d}\quad（0°和90°方向）\tag{1}$$

$$\sigma_{正}=\frac{1}{1.4d}\quad（45°和135°方向）\tag{2}$$

When using the hexagonal combination, the limit resolution is

采用六边形的组合方式时，其极限分辨率为

$$\sigma_{六}=\frac{1}{\sqrt{3}d}\quad（0°、60°和120°方向）\tag{3}$$

$$\sigma_{六}=\frac{1}{d}\quad（30°、90°和150°方向）\tag{4}$$

After determining the arrangement structure and the diameter of the fiber image transmission beam, the minimum limiting resolution of the fiber image transmission beam can be calculated. To improve the image

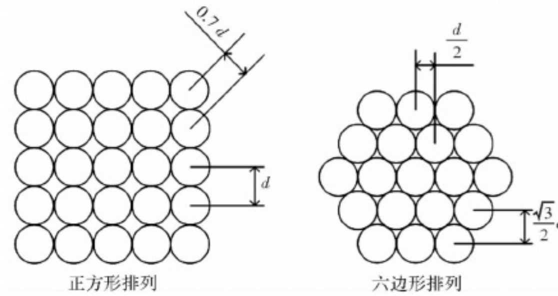

Figure 3 The arrangement of the optical fiber image transmission bundle

Fig. 3 Arrangement of imaging fiber bundle

The image quality of the imaging fiber bundle needs to meet the requirement that the modulation transfer function (MTF) value of the designed objective lens is high at this limit resolution.

2 Design Example

According to the performance requirements of the actual endoscope, an optical fiber beam with an outer diameter of 0.64 mm and a monofilament diameter of 7.5 ym was selected. Under the static condition, the ultimate resolution of the image beam was 77 lp/mm when the optical fiber was arranged according to the hexagonal shape. Therefore, the preset objective lens was designed based on the optical fiber image transmission beam, which required the modulation transfer function (MTF) value of 0.7 at the limit resolution of 77 Ip/mm, the working wavelength (0.48-0.65) um, the object field Angle 20= 90°, the object is 25 mm, and the focal length f'= 0.37 mm can be obtained by Gaussian formula. The relative aperture D/f'=1/4 was chosen according to the requirements of size and depth of field of endoscope in practical use, and to ensure that the numerical aperture of the image beam was not less than that of the preset objective

The current technology requires that the diameter of the front lens is not less than 0. 5 mm, the radius of curvature must be more than 0.4 mm, the thickness of the lens must be controlled within 0.3 mm~0.5 mm, and the edge thickness and spacing are required to be more than 0.15 As shown in Figure 4, the objective optical system composed of four lenses is the result obtained after optimization of the calculation and optical simulation software. When choosing the lens material, high refractive index low dispersion of H - ZLaF68 shaft beam and shaft outside the beam incident Angle rapidly decreases, and increased relative aperture and field of view, is beneficial to increase the glass curvature radius at the same time, to reduce the senior aberration. The H-KF6 lens is beneficial to achromatic aberrations. In addition, H-ZLaF50D glass is used in double glue lenses in conjunction with heavy flint D-ZF94 glass. The total optical length of the objective lens is 3.9 mm, and the maximum cross section diameter is 0.95 mm, which meets the requirements of the image side telecentric optical path system. According to the Zemax optical simulation software, the numerical aperture of the object mirror is 0.09, which is smaller than the numerical aperture of the optical fiber, and conforms to the law of total reflection of the optical fiber, so the incident beam can completely enter the optical fiber image beam.

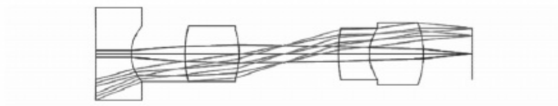

FIG. 4 Objective lens of fiberoptic endoscope

Fig. 4 Objective lens for fiber-optie endoscope

The front group of the optical system is composed of a negative lens with negative focal power, and the back group is composed of a positive lens and a double glue lens. Placing the lens with negative focal degree in the front group can effectively reduce the Angle of view of the back group, so that the optical system can obtain a larger field of view. And the negative lens of the front group and the double glue lens of the back group play an important role in correcting the chromatic aberration and the field curvature of the whole optical system. In order to form the image side telecentric optical path system, the aperture light bar is placed at the front focus of the double glue lens

As shown in Figure 5, the modulation transfer function (MTF) curve of the front objective optical system is the main method to evaluate the imaging quality of the optical system. Figure 5 shows that the modulation transfer function (MTF) value of the objective lens at the Nyquist spatial frequency of 77 lp/mm is close to 0.7, which meets the image quality requirements.

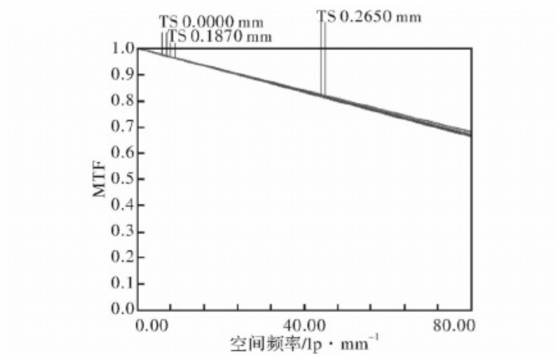

Figure 5 Modulation transfer function curve

Fig.5 Curve of MTF

Figure 6 is the dot sequence diagram of the optical system. It is known that the size of the single fiber of the image transmission beam is 7.5 m. According to the dot sequence diagram, the maximum radius of the geometric dispersion spot of the optical system is 0.885 ym, which meets the requirements of imaging quality.

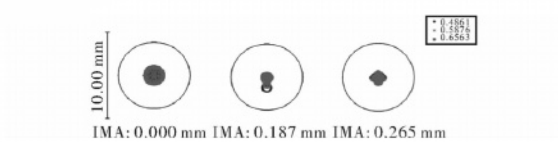

Figure 6 column chart

Fig. 6 Spot diagram

Figure 7 shows the energy concentration distribution curve of the optical system, and the abscisordinate and ordinate are the image spot diameter and energy concentration, respectively. Figure 7 shows that more than 95% of the energy is mainly concentrated in the circle with a diameter of 20 um, and 90% of the energy is mainly concentrated in the circle with a radius of 3 um.

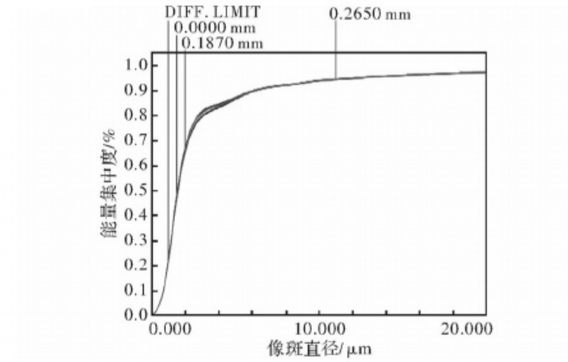

Figure 7 Energy concentration curve

Fig. 7 Curve of encircled energy

According to the analysis of Zemax software, the relative illuminances of the on-axis and off-axis beams on the image plane are evenly distributed, which meets the requirements of the telecentric optical path system on the image side. The maximum distortion of the system is -18.8% at the outermost edge ray. In order to meet the wide-angle performance requirements of the optical system, the "negative-positive" type optical structure is used, which will inevitably produce large distortion. As an observation system, the endoscope will not affect the imaging clarity of the system, and the distortion can be corrected by image processing algorithm in the later stage to meet the best imaging quality requirements [13].

3 Conclusion

As the key part of the image system of fiberoptic endoscope, the design of the objective lens should be based on the structure and size of the optical fiber and the performance requirements of the endoscope. The preset objective lens should first meet the full reflection condition of the optical fiber. The "negative-E" type image side telecenter system is selected to ensure the large field of view, small size and image plane uniformity of the preset objective optical system. In the structure of the objective lens, the double glue lens is used to correct the aberration of the optical system and improve the imaging effect of the front objective lens. The design example in this paper shows that the design idea is feasible.

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